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US ARMY TEST & EVALUATION COMMAND

REPORT ON USATECOM PROJECT NO. 1-3-7870-03-A

RESEARCH TEST TO EVALUATE THE TECHNIQUES AND PRECISION OF THE MEASUREMENT OF SMOKE FROM DIESEL ENGINES

REPORT NO. DPS-1204

MARCH 1964

DEVELOPMENT AND PROOF SERVICES
ABERDEEN PROVING GROUND, MARYLAND

HEADQUARTERS

U.S. ARMY TEST AND EVALUATION COMMAND

Aberdeen Proving Ground, Maryland 21005

AMSTE-BB 3-7870 10 APR 1964

SUBJECT: Report on USATECOM Project No. 1-3-7870-03-A, Research Test To Evaluate the Techniques and Precision of the Measurement of Smoke from Diesel Engines (DA Project No. 1A024401A106)

TO: Commanding General
US Army Materiel Command
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FOR THE COMMANDER:

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ABSTRACT

Smoke from diesel engines is a major problem to both commercial and military fleet operators. Methods of measurement have been varied with no precision of measurement established and no means of correlating results between methods. The Army and industry joined on a cooperative project to evaluate the many instruments available, to establish operating and sampling techniques, and to establish a common set of units or scale to define smoke. It has been shown that each of the basic types of smokemeters produced commercially have a definite area of application and that all are required. Smokemeter operating techniques have been established but sampling techniques can only be indicated in general terms at this time. A common smoke density scale has been established. It is recommended that smoke should be sampled, measured, evaluated, and expressed as established by the Smokemeter Group, Diesel Vehicle Fuel, Lubricant and Equipment Research Committee of the Coordinating Research Council, Inc.

REPORT ON USATECOM PROJECT NO. 1-3-7870-03-A

RESEARCH TEST TO EVALUATE THE TECHNIQUES

AND PRECISION OF THE MEASUREMENT OF

SMOKE FROM DIESEL ENGINES

REPORT NO. DPS-1104

Test Director: D. E. Wommert
Engineering Laboratories
Development and Proof Services
Aberdeen Proving Ground, Maryland
AMCMS Code No.: [illegible]
DA Project No.: [illegible]

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PART I - GENERAL

1.1 Authority

1.1.1 Directive. This test was authorized under AMCMS Code No. 5025.11.800.

1.1.2 Purpose of Test. The broad objective was to establish a technically sound and exactly defined method of measuring the density of smoke from diesel engines in laboratory tests. Specific objectives were to establish the following:

a. The magnitude and source of error encountered in smoke measurement.

b. A uniform smoke scale with correlation factors for each specific type meter.

c. The relationship between density and visual evaluation of the engines tested.

d. The exact operating techniques for commercially available meters.

e. Reasonable limits for an acceptable sampling technique.

1.2 Description of Materiel

In smoke measurement, there are three areas which are generally independent in the physical sense but closely interrelated in that each has a decisive effect on the final smoke value. The first is the source of smoke - the engine and exhaust system. The second is the sampling system - the probe, probe location, condensate trap, sample tube, and surge tank. The third is the smokemeter - that instrument used to obtain the sample and evaluate it.

1.2.1 Source of Smoke. This is normally fixed and, in the usual case, is the item or system to be evaluated. The combustion system, the exhaust system, the engine load factor, and other engine features have a decided effect on the type of smoke and the intensity of it. Five diesel engines and four diesel-powered vehicles were utilized in the tests and are described in Table I. The engines were types that both vaporous and particulate smoke could be evaluated. The engines were mounted on dynamometer stands so that load and speed could be varied to provide smoke which ranged from just visible to dense.

Table I. Engine and Vehicle Description

Laboratory Engines

Manufacturer	Continental	Continental	Cummins	Ford	GM
Model	AVDS-1790-2	LDS-427	C-200A	XMDVS-534-2-15	4-53
No. of cylinders	12	6	6	8	4
Cycles	4	4	4	4	2
Bore x stroke, in.	5.75 x 5.75	4.31 x 4.87	4.437 x 5	4.5 x 4.2	3.875 x 5.5
Displacement, cu in.	1790	427	464	534	213
Max rated speed, rpm	2400	2600	2800	3000	2200
Supercharger	Turbo	Turbo	Turbo	None	Mech
Cooling	Air	Water	Water	Water	Water

Vehicles

Vehicle	Truck, cargo 2-1/2 ton, 6x6 M35A1	Truck, cargo 5-ton, 6x6 M54E3	Truck, cargo 8-ton, 4x4 XM520E1	Tank, combat tracked, M60
Gross vehicle weight, lb	13,600	20,000	26,600	103,000
Max road speed, mph	55	54	32	30
Engine				
Manufacturer	Continental	Mack	Caterpillar	Continental
Model	[a]LDS-427	ENDT-673	D-333	[a]AVDS-1790-2
No. of cylinders	6	6	6	12
Cycles	4	4	4	4
Bore x stroke, in.	4.31 x 4.87	4.875 x 6	4.5 x 5.5	5.75 x 5.75
Displacement, cu in.	427	673	525	1790
Max rated speed, rpm	2600	2100	2400	2400
Supercharger	Turbo	Turbo	Turbo	Turbo
Cooling	Water	Water	Water	Air

[a]Same engine as described under laboratory engines.

1.2.2 Sampling Equipment. The method of sampling plays an important role simply because it is necessary to obtain a typical smoke sample if a reasonable estimate is to be made of the smoke density at the engine tailpipe. After a sample is obtained, it then becomes necessary to transport that sample to the meter without altering the characteristics of the sample. The sampling equipment shown in Figure 1 was used at two locations on each engine. The locations were the downstream side of the flange and 3 feet downstream from the flange. Exhaust collected at the probe passed through the sample line to a surge tank. The four sample taps on each surge tank permitted four simultaneous observations to be taken of exhaust from one location. Samples from vehicles were taken at the end of the exhaust pipe. Three types of probes were used on the engines (Figure 2). Either a Bosch probe or no probe was used on the vehicles.

1.2.3 Smokemeters. There are three basic types of smokemeters - light extinction, continuous filtering, and spot filtering. Each has its own particular advantages and disadvantages. While each has its own area of preferred application, there is much overlap and many instances where the choice is arbitrary.

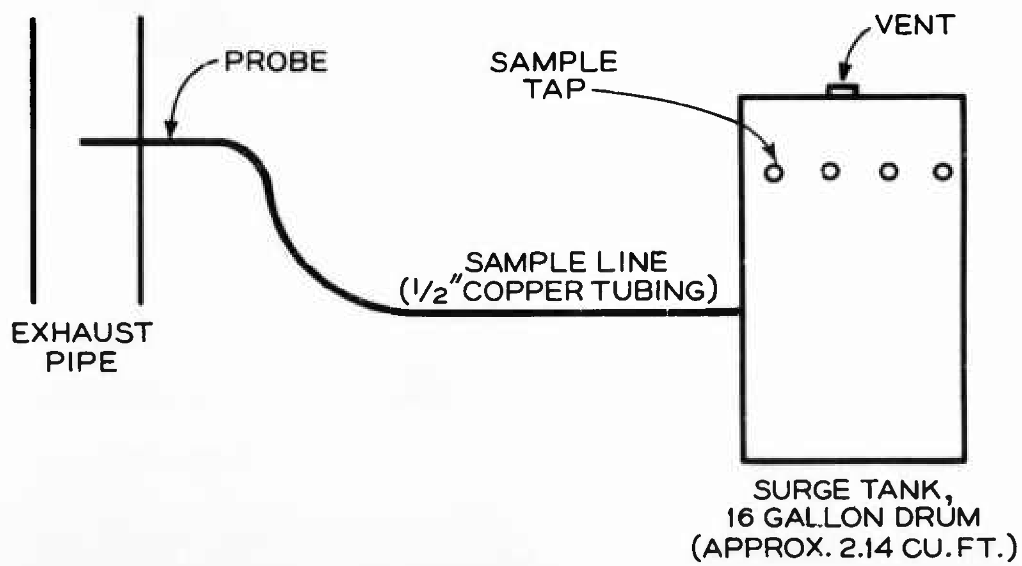

Figure 1: Exhaust Sampling Equipment.

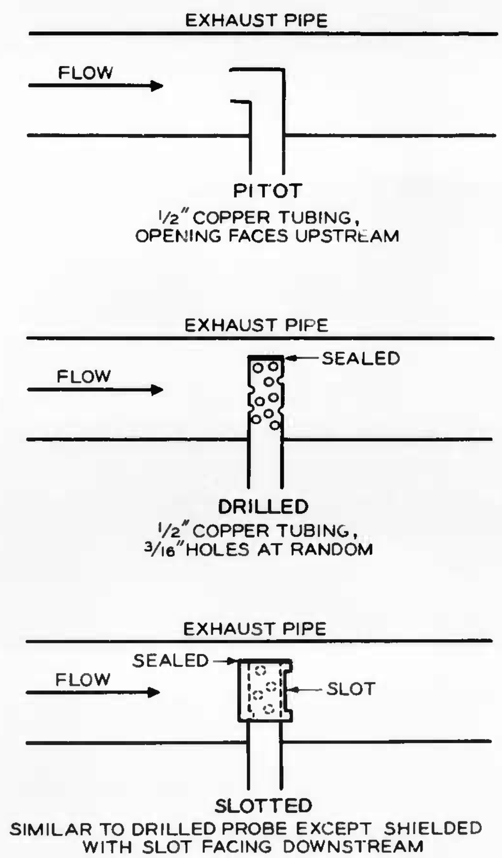

Figure 2: Probe Types

Twenty-seven smokemeters (ten light extinction, eight continuous filtering, and nine spot filtering) were furnished for the tests by the participants. Eight of each type were used for the experimental work and three were held in reserve. The smokemeters are described in Table II. Those designated as experimental were unique laboratory instruments that are not commercially available. Typical smokemeters are illustrated in Figures 3 through 7. Figure 8 shows a photoelectric device used to evaluate continuous filter types.

Table II. Smokemeter Descriptions

Manufacturer	Type	Description
Experimental (American Oil Company)	Light Extinction	18 in. tube length, sample and purging pump
Experimental (California Research Corporation)	Light Extinction	6 in. tube length, purging pump
Experimental (Caterpillar Tractor Company)	Light Extinction	30 in. tube length, purging pump
B-P Hartridge	Light Extinction	18 in. tube length, purging pump
Photovolt	Light Extinction	18 in. tube length, purging pump
Von Brand Filtering Recorders	Continuous Filtering	2 in. per minute tape speed, single trace
Von Brand Filtering Recorders	Continuous Filtering	2 in. per minute tape speed, dual trace
Von Brand Filtering Recorders	Continuous Filtering	4 in. per minute tape speed, single trace
Experimental (International Harvester Company)	Continuous Filtering	4 in. per minute tape speed, single trace
Bacharach Industrial Instrument Company (Prototype Model)	Spot Filtering	Spring driven pump 5/8 in. spot diam (approx)
Robert Bosch Corporation	Spot Filtering	Spring driven pump 1-1/4 in. spot diam (approx)

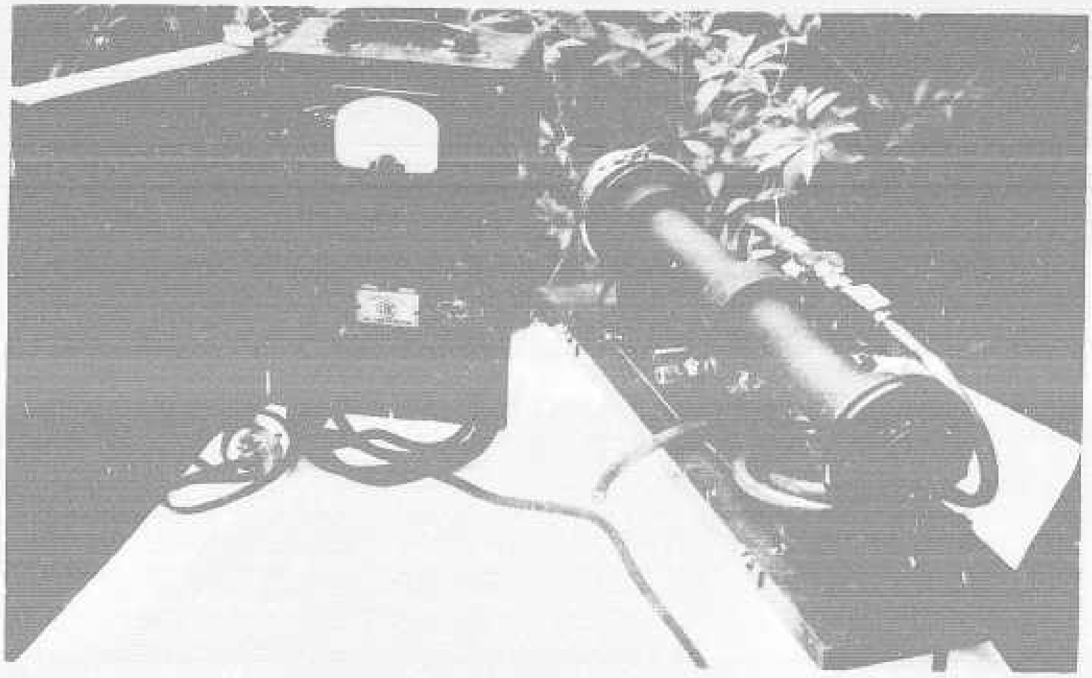

Figure 3: Photovolt Smokemeter (Light Extinction).

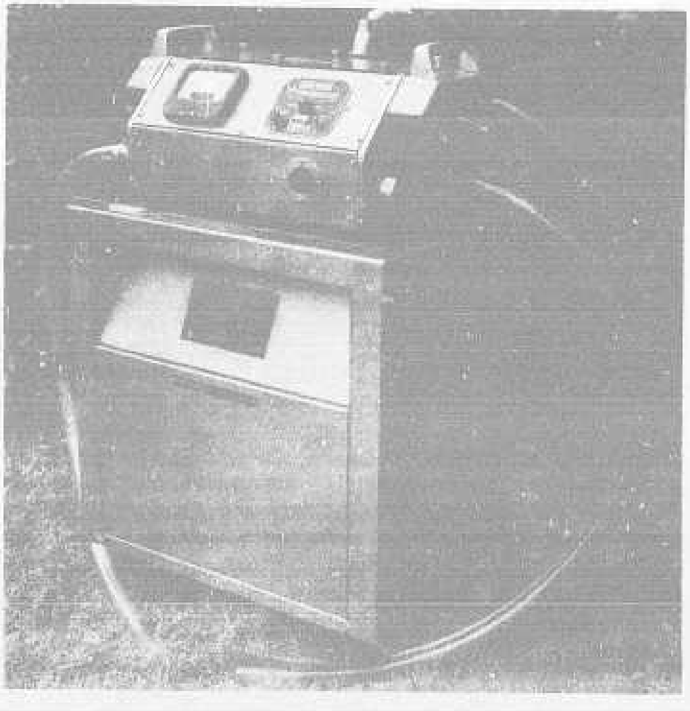

Figure 4: BP Hartridge Smokemeter (Light Extinction).

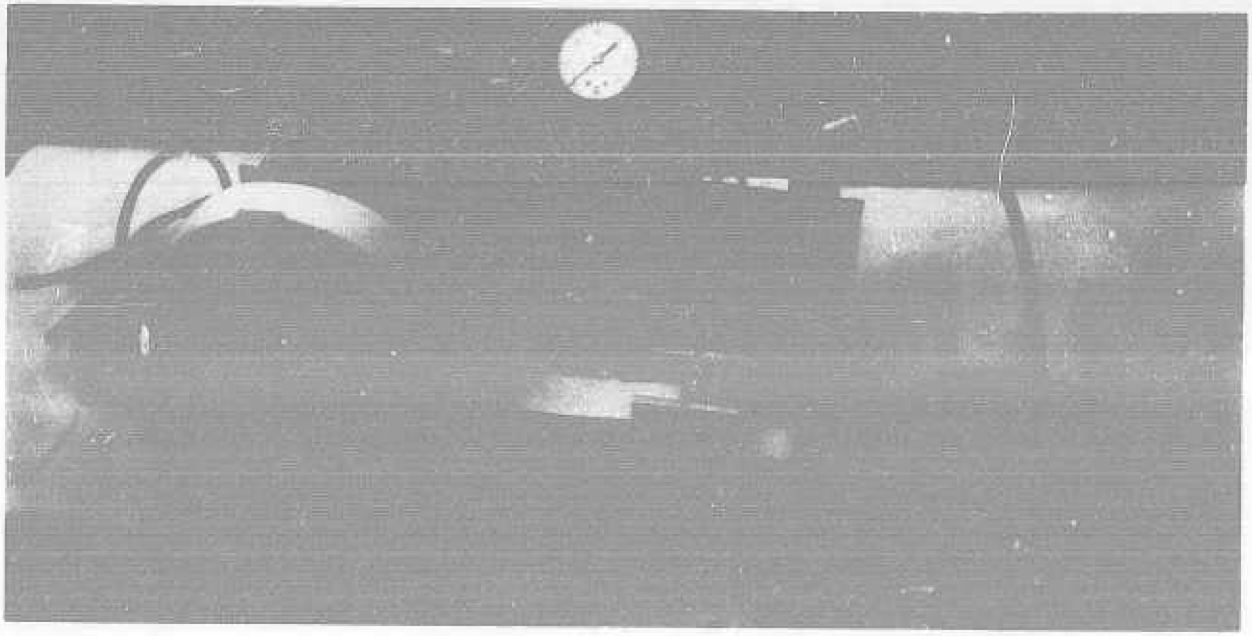

Figure 5: Von Brand Smokemeter (Continuous Filter).

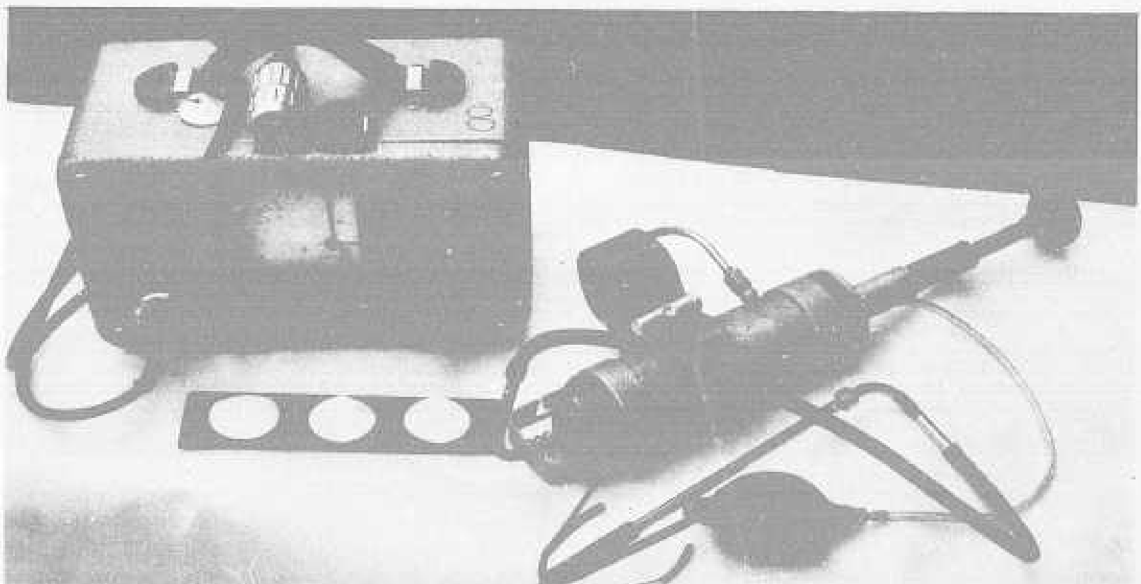

Figure 6: Robert Bosch Smokemeter (Spot Filter), Reflectometer and Probe.

Figure 7: Bacharach Smokemeter (Spot Filter) and Probe.

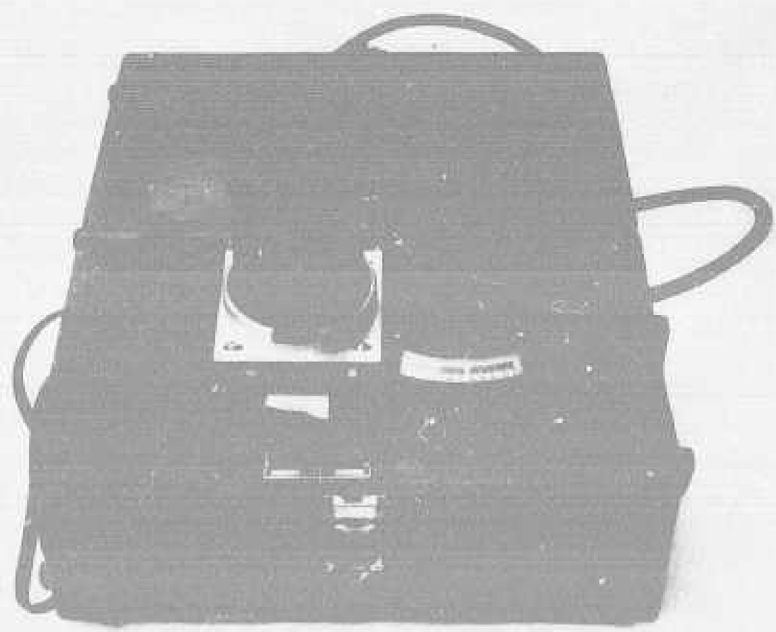

Figure 8: Photovolt Reflectometer (Tape Analyzer).

1.3 Background

Smoke emanating from a diesel engine is of prime concern to a fleet operator whether it be a commercial or military operation. Smoke is an indication that the engine is in need of maintenance or that it is being overloaded. Generally, smoking conditions are conditions which lead to poor fuel economy. The contamination of the atmosphere is becoming more serious each year; the role diesel smoke plays in this contamination is not the subject of this report except to note that it is a factor. Of importance to the military is the ease with which a convoy may be detected when one or more of the vehicles are smoking.

A major problem exists in that there is no common language to describe smoke and no consistent technique to be used in measuring smoke. There are numerous instruments for measuring smoke; three different basic principles of operation are involved along with several subtypes. Different probes and sampling techniques are recommended; different means of evaluation and different rating scales are utilized. In the course of time, experience has shown that no one of these meters is superior to the others and that no organization is justified in specifying the use of one to the exclusion of the others.

Work and testing within the framework of The Smokemeter Group of the Diesel Vehicle Fuel, Lubricant, and Equipment Research Committee of the Coordinating Research Council led to the recognition of the need for obtaining and disseminating information on proper operation of smokemeters, acceptable sampling techniques, and a means for reporting data on some uniform smoke scale.

In 1962, a cooperative project between the Army and industry was established within the Coordinating Research Council (CRC), to fulfill this need. The material presented in this report is a concise summary of the test work conducted at Aberdeen Proving Ground. Reference 1 is recommended for the detailed discussion of the test and over-all smoke measurement problem.

1.4 Summary of Findings

The sources of error have been identified and their magnitude has been determined. The error is about 5% of the normal working range of smoke levels.

A basis for a common expression of smoke density has been established with correlation factors for each meter. More extensive work will be required to provide the necessary precision and confidence.

Visual ratings have been shown to be very dependent on surrounding factors and an unreliable means of defining smoke.

Operating techniques for the smokemeters were shown to be adequate.

A good maintenance program is a big factor to satisfactory smoke measurements.

Sampling continues to be a major problem. Only general guide lines may be established because each engine presents a different situation with respect to velocities and flow patterns.

1.5 Conclusions

It is concluded that:

a. Of the three basic types of smokemeters being produced commercially, none is superior in all respects; each fulfills a specific need.

b. Visual ratings are not sufficiently precise for laboratory purposes.

c. There is a sound basis for a uniform or commom smoke scale. The term smoke density as defined by the Beer-Lambert law is satisfactory.

1.6 Recommendations

It is recommended that:

a. Smoke should be sampled, measured, evaluated, and expressed as established by the Smokemeter Group, Diesel Vehicle Fuel, Lubricant and Equipment Research Committee of the Coordinating Research Council, Inc. The current recommendations of this group are expressed in Reference 1.

b. Visual ratings should not be used for laboratory evaluations.

c. Requirements for smoke in engine specifications should not be stated in visual terms.

d. Techniques and precision of data should be studied for field applications.

e. A transition to utilizing the common smoke density scale should be started with an eventual objective of reporting all data in these terms.

SUBMITTED:

D. E. WOOMERT
Test Director

REVIEWED:

R. W. JOHNSON
Chief, Automotive
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Chief, Engineering Laboratories

APPROVED FOR THE DIRECTOR,
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R. P. WITT
Assistant Deputy Director
for Supporting Services

PART II - DETAILS OF TEST

2.1 Procedure

Prior to the test, each smokemeter was checked for mechanical condition and operation. Operating instructions supplied with the instruments were checked to be sure they were adequate. This was accomplished by teams of observers. (Observers for this test consisted of engineers from the participating organizations.)

Light extinction meters were calibrated and standardized in terms of ten Kodak neutral density filters in equal steps from 0.1 to 1.0 units.

The main experimental tests were designed to provide most of the data necessary to meet the objectives. The observers and smokemeters were divided into five groups to match the five engines. The observers rotated as a group so that they devoted a half day collecting data on each engine. Smokemeters were rotated at the same time, but this was done on an individual basis in a random fashion rather than as a group. Each group of observers took data on a prescribed schedule which included some replicate runs. For each engine-observer-smokemeter combination the engine was operated at differing loads to produce different intensities of smoke. All four smokemeters in a group were read simultaneously. Where the test setup permitted, visual observations of density and color were recorded.

Vehicles were operated on a straight, level test track. No particular rotation of observers or meters was followed.

Several secondary tests were conducted to determine whether smoke intensity drifted systematically with time during prolonged operation and to determine the effect of vacuum versus tape speed on the continuous filtering meters.

All data were punched in cards and eventually handled in a computer by one of the participants. Statistical methods were used to examine the data to establish the source and magnitude of error and to establish the meter correlations.

For purposes of card punching and to preserve anonymity, all observers, smokemeters, and engines were assigned code numbers which were used throughout the test and analysis.

2.2 Results

2.2.1 Source of Error. The total error in an observation made with a smokemeter may be a result of error variation stemming from several sources. These are:

a. Short Term Error. The variation among observations taken by one observer with a smokemeter over a short period of time. It may be caused by inconsistent reading of the scale or meter and engine fluctuations.

b. Observer Error. The variation among observations taken by more than one observer. It may be caused by differences in ability, dexterity, and judgment among people.

c. Meter Error. The variation among observations taken with more than one smokemeter. It may be caused by differences in mechanical condition, calibration, and tolerances among smokemeters.

d. Observer Times Meter Error. The variation due to the interaction of observers with smokemeters.

e. Observer Times Condition Error. The variation due to the interaction of observers with conditions.

f. Meter Times Condition Error. The variation due to the interaction of smokemeters with conditions.

Of these, only the short term error was found to be a significant source of error. In addition probe location appeared as a significant source of error.

2.2.2 Magnitude of Error. An analysis of the short term error is presented in Table III. The mean observation is the mean of all the data taken during the main test program with a given type of smokemeter and the range is the highest observation minus the lowest observation encountered. Data for the light extinction meters were broken down three ways because there was a significant difference in the standard deviation with the experimental A and G (the letters refer to the assigned codes) meters and a significant difference in the mean level of smoke recorded with the experimental E meters.

Data taken during the vehicle phase of the test were not sufficient to partition the results to determine the source of error. Total error is presented in Table IV. Because conditions of operations are completely different, it is conceivable and probable that short term error is not the only significant source. All the errors previously mentioned may be present. The error encountered in reproducing vehicle conditions is likely to be high. Simultaneous readings were not made in this phase.

Table III. Short Term Error (Determined in the Laboratory)

Meter Type	σ	σ,% of Mean	σ,% of Range	Mean	Range
Light Extinction:					
Commercial	0.038	14	4	0.28	0.95
Experimental A, G	.065	23	7	0.28	0.95
Experimental E	.022	16	6	0.14	0.34
Continuous Filtering:					
2 in./min, 1 in. Hg	253	7	4	3.53	6.80
2 in./min, 2 in. Hg	.287	7	4	4.31	7.10
4 in./min, 2 in. Hg	.205	6	3	3.30	6.60
4 in./min, 5 in. Hg	.262	6	3	4.14	7.90
Spot Filtering, 1-1/4 in. diam	.149	10	3	1.49	4.80
Spot Filtering, 5/8 in. diam	.291	14	5	2.03	5.40

Table IV. Total Error (Determined on Vehicles)

Meter Type	σ	σ,% of Mean	σ,% of Range	Mean	Range
Commercial Light Extinction	0.252	43	11	0.584	2.19
Continuous Filtering 2 in./min, 1 in. Hg 4 in./min, 2 in. Hg	1.220	22	18	5.633	6.70
Spot Filtering, 1-1/4 in. diam	0.917	27	16	3.417	5.60

2.2.3 Uniform Expression. Observations taken with different smokemeters will differ because different units or different scales are used. To obtain a means of uniform expression, a single scale and set of units must be established. The density unit used with the Kodak neutral density filters has a fundamental basis in the Beer-Lambert law. This is expressed as

$$\ln \frac{I}{I_o} = - kLc$$

or

$$\log \frac{I_o}{I} = 0.453\ kLc$$

where:

I = Light leaving sample of light-absorbing material.

I_o = Light entering sample of light-absorbing material.

k = Absorption coefficient of material.

L = Length of light path through material.

c = Concentration of material.

In this relationship, the k and c are a function of the smoke and may be combined into a single constant - the density. The L is a function of the smokemeter. For light extinction meters which are based on this principle, it would be a simple matter to express data in terms of an L = 18 inches, which is commercially available and is most common.

$$O_L = S\ d$$

where:

O_L = Observation with smokemeter of length L

d = Smoke density = kc

S = Scaling factor = $\frac{L}{18}$

The evaluation of a filter from a filtering type smokemeter with either a light reflectance or light transmission instrument is based on the relation

$$R = \left(\frac{I_o - I}{I_o}\right) 10$$

where:

R = Light absorbed on a zero to 10 scale.

It can be shown that

$$\log \frac{10}{10-R} = S\ d$$

By relating values of R obtained on a filtering meter and values of d obtained on a light extinction meter, an effective scaling factor may be determined for filtering smokemeters. This was done by regression techniques using mean values. Results are shown in Table V and presented as a nomograph in Figure 9. The 95% confidence limits are for a sample size of six to ten. Only those meters which are commercially available were included. Statistical checks show that the relationship is correct, but the standard errors (about 15% to 25% of the mean density) indicate poor precision in defining the scaling factors.

Table V. Effective Scaling Factor, S

Smokemeter	S	σ	95% Confidence Limit[a]
Continuous Filtering			
2 in./min, 1 in. Hg	1.235	0.053	± 0.106
2 in./min, 2 in. Hg	1.600	.056	± .087
4 in./min, 2 in. Hg	1.103	.001	± .022
4 in./min, 5 in. Hg	1.395	.043	± .077
Spot Filtering			
Robert Bosch	0.468	.025	± .131

[a]Confidence limit on predicted density based on a mean of at least six to ten observations.

2.2.4 Visual Evaluation. In designing the test program no effort was made to evaluate the effect of color, background, and lighting on the visual smoke rating. The existence of these effects, as well as smoke density, was recognized and recorded. Figure 10 indicates that observers agree more on smoke of high intensity than on smoke of low intensity.

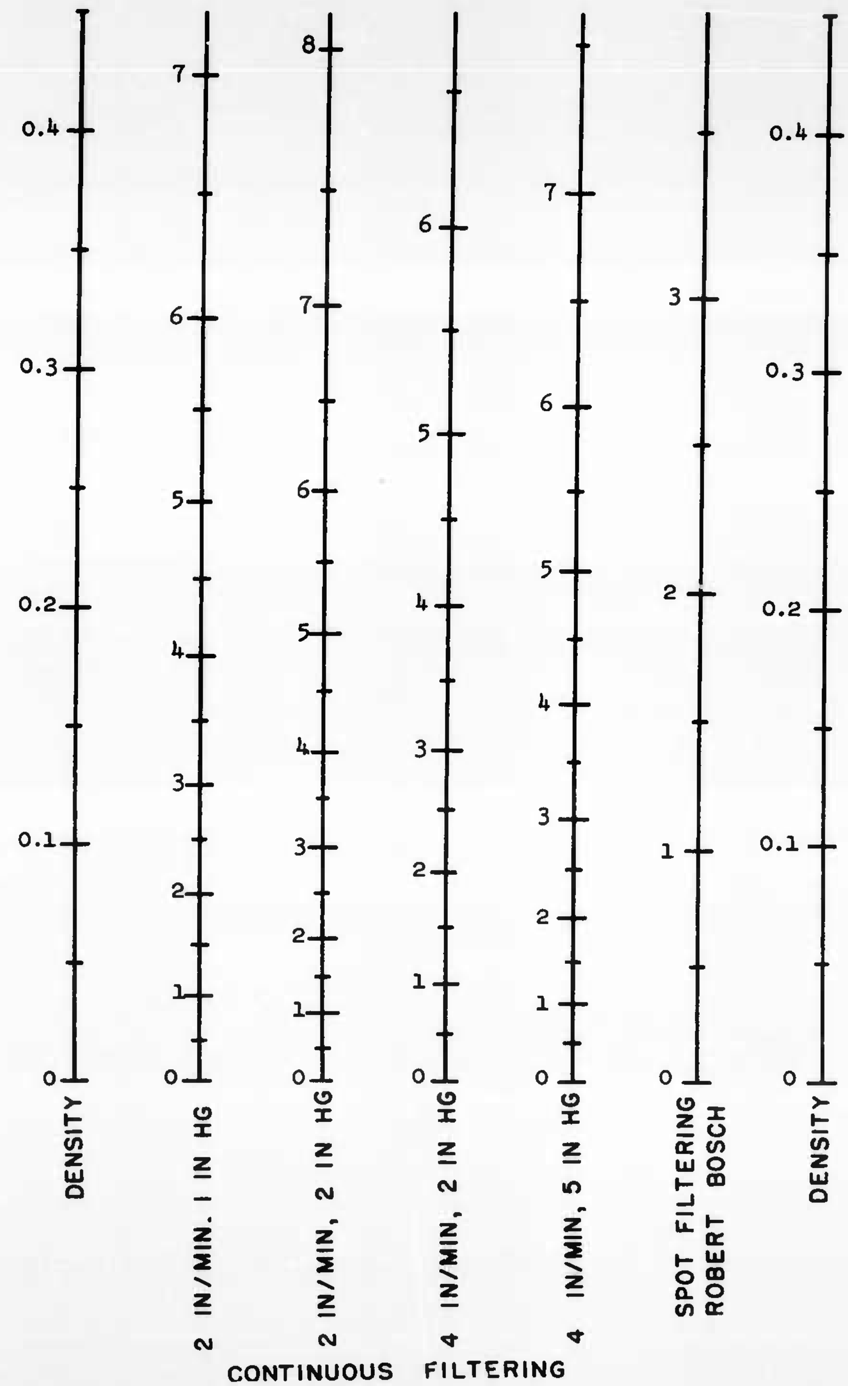

Figure 9: Smokemeter Scale Correlations

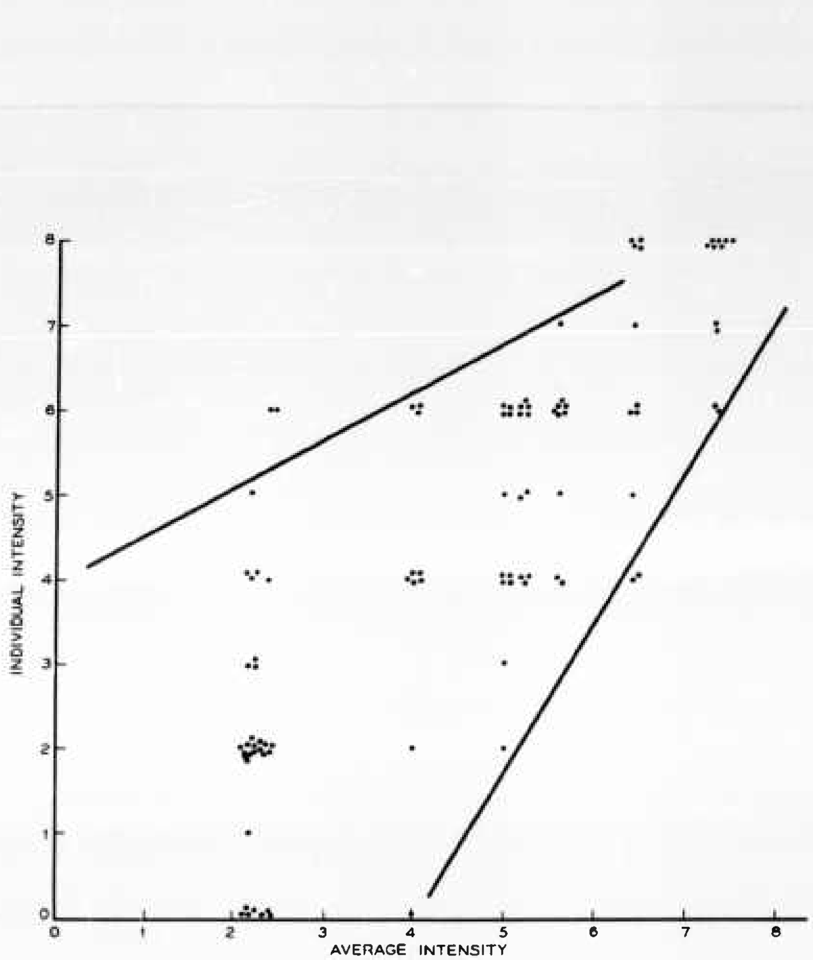

Figure 10: Effect of Intensity on Range of Visual Ratings.

2.2.5 Smokemeter Operating Techniques. In all cases, the manufacturer's operating instructions were adequate. Suggestions for change or refinement of procedure amounted only to an emphasis of points already covered in the procedure.

2.2.6 Sampling. The data indicate that the probe location may affect the results by at least 15%; however, the sampling point to yield the highest value is dependent on the engine and exhaust system. The data on probe type were limited and produced inconclusive results. There was no systematic drift with prolonged operation.

2.3 Discussion

It was apparent in the results of these tests that the best visual evaluation that can be made by different observers under all conditions is light, medium, and heavy smoke. The ability to distinguish color is very much dependent on background and to some extent lighting (both degree and direction). Shown in Figure 11 is the effect of background on the type of smoke seen; included is a comparison with two types of smokemeters. Filtering meters are capable of screening only particulate (black) smoke; light extinction meters will sense both

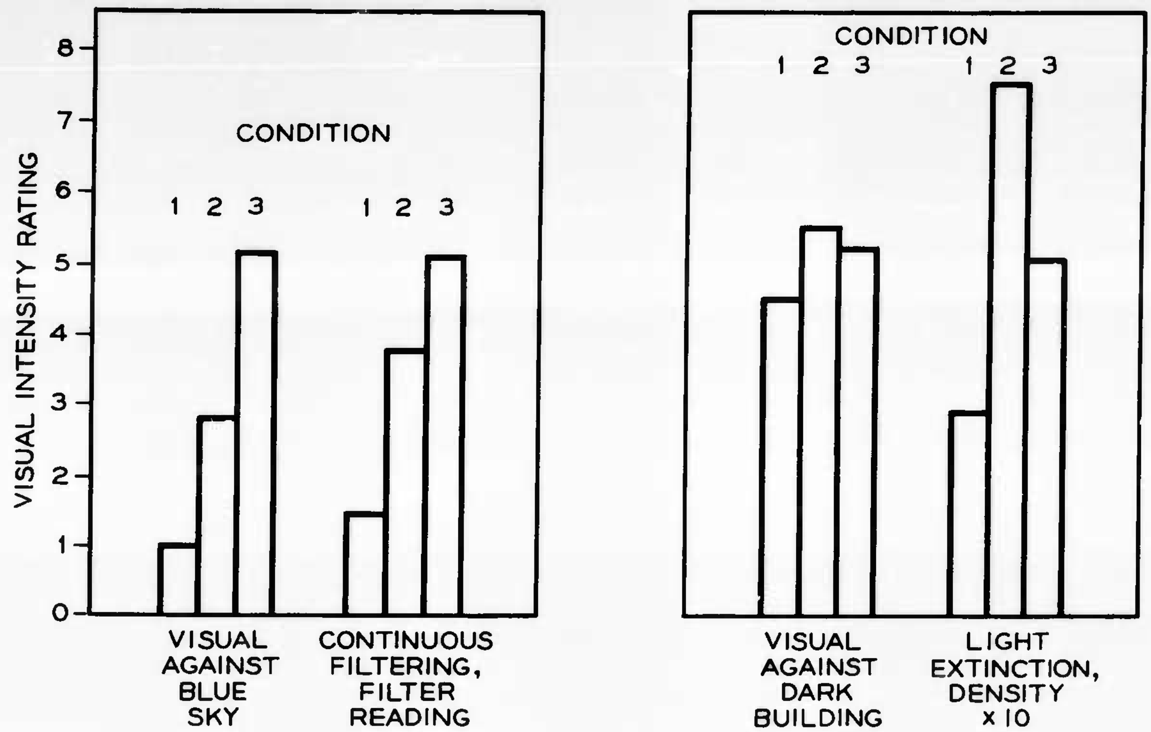

Figure 11: Effects of Background (Engine 1).

vaporous (blue or white) smoke and particulate smoke. When an observer rates against a light sky, he sees smoke in the manner of a filtering smokemeter. When the observer rates against a dark background, he sees only the blue or white component found in the light extinction meter.

The use of a smokemeter will permit a finer definition of smoke. A smokemeter should be used whenever any degree of accuracy is required. No particular meter is superior to another; each has advantages and disadvantages which will dictate the use of a particular meter for a particular situation.

The choice of a meter because of a particular set of units or scale is no longer justified since conversion is possible. In applying these conversion factors (or using the nomograph), it must be remembered that they were developed on the basis of a large sample size; the 95% confidence limits are on the basis of a sample size of six to ten. A minimum sample size of three should be used and the average should be reported. Photoelectric means should be used to evaluate filters. Where such a device is not available the following relationships may be used to relate Bacharach grey scale values to reflectance readings. It must be remembered that there is an additional source of error in this process.

Spot filtering relationship:

$$R_s = 0.097\ G - 0.127$$

$$R_s = 0.6$$

where:

R_s = Estimated reflectance reading.

G = Bacharach grey scale value (Model RR-776).

Continuous filtering relationship:

$$R_c = 0.94\ G - 0.41$$

$$R_c = 0.6$$

where:

R_c = Estimated reflectance reading.

G = Bacharach grey scale value (Model RR-776).

Detailed operating instructions for the smokemeters as supplied by the individual manufacturers are satisfactory. Maintenance is a prime factor in assuring reliable readings. Sampling techniques have not been and cannot be

specified in detail at this time. Each engine and exhaust system must be considered separately. The probe should be located at a point where there is little or no stratification of the exhaust. Moisture disturbs the function and proper reading of all smokemeters and should be eliminated. Line length and diameter must be considered to be assured of a typical sample being analyzed at the meter. The choice between direct and indirect sampling (surge tank technique) is dependent on the individual situation. For instance, fast response to measure transient conditions can only be accomplished by direct means. Indirect sampling permits a larger sample and improves the probability of obtaining a typical sample.

PART III - APPENDIX

APPENDIX A

Reference

1. CRC Report No. 371, "1962 Smokemeter Tests," SAE General Publications Department, 485 Lexington Avenue, New York 17, New York.

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USATECOM PROJECT NO. 1-3-7870-03-A, RESEARCH
TEST TO EVALUATE THE TECHNIQUES AND PRECISION
OF THE MEASUREMENT OF SMOKE FROM DIESEL ENGINES
D. E. Woomert

Report No. DPS-1204, March 1964
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Unclassified Report

The Army and industry joined on a cooperative project to evaluate the many instruments available, to establish operating and sampling techniques, and to establish a common set of units or scale to define smoke. Smokemeter operating techniques have been established but sampling techniques can only be indicated in general terms at this time. Research findings and recommendations are found in this report.

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